



Thermo-mechanical evaluation of self-healing metallic structures for aerospace vehicles utilizing shape memory alloys

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Outline

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- The innovation: SMASH technology
- Liquid-assisted self-healing approach
- Impact of the innovation
- Results of the Seedling Phase I effort
- Distribution/dissemination
- Future work



Shape Memory Alloy Self-Healing (SMASH) Technology

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- Designing and testing an aeronautical lightweight structural alloy with self-repairing capabilities
 - Materials system can self-repair cm-long cracks
 - Investigation focused on self-repair of fatigue cracks
 - Aluminum alloy matrix reinforced with high-strength shape memory alloy (SMA) elements
 - Thermodynamic approach to design matrix alloy with pre-determined fraction of low melting eutectic phase



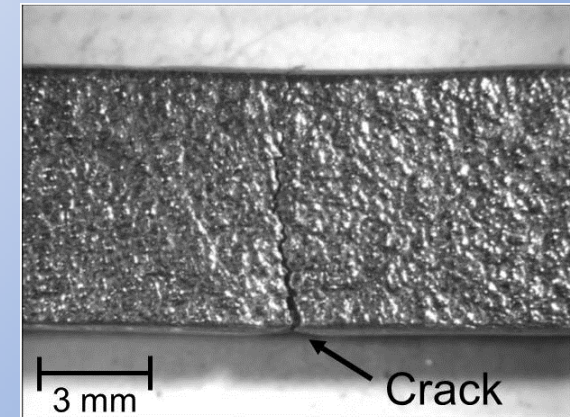
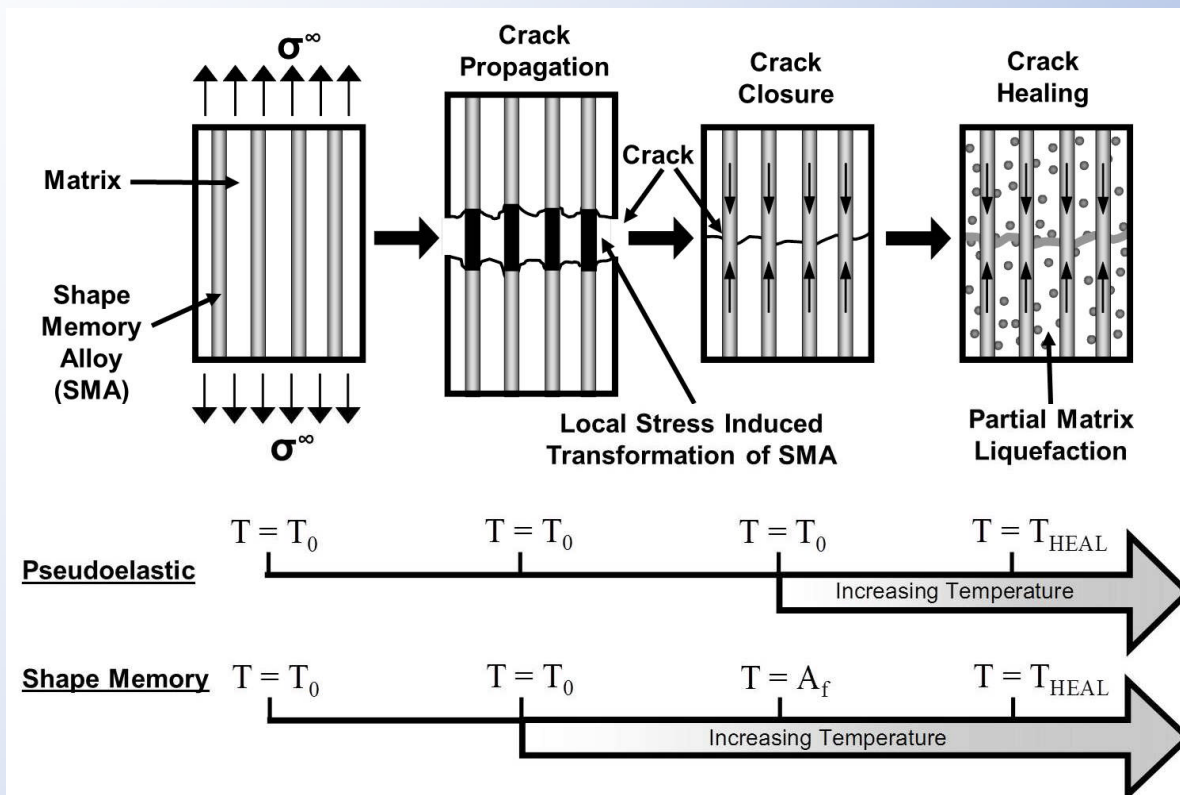
M. Creps et. Al., Incorporating Aluminum Hybrid Materials to Facilitate Life Extension in Legacy Aircraft, Airworthiness 2012 proceedings



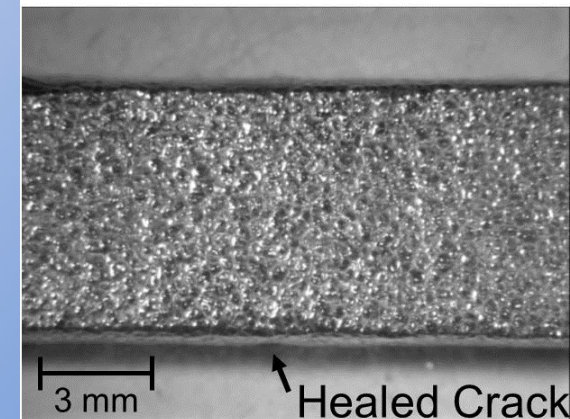
Liquid-Based Self-Healing of Metal-Metal Composites

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- Clamping force from the SMA wires
- Partial liquefaction of the matrix



a)



b)

Manuel, M.V, *Principles of Self-Healing in Metals and Alloys: An Introduction*, Chapter in *Self-Healing Materials: Fundamentals, Design Strategies and Applications*, Ghosh, S. K., Ed. Wiley: 2008;.

July 9-11, 2013

NASA Aeronautics Mission Directorate FY12 Seedling Phase I Technical Seminar

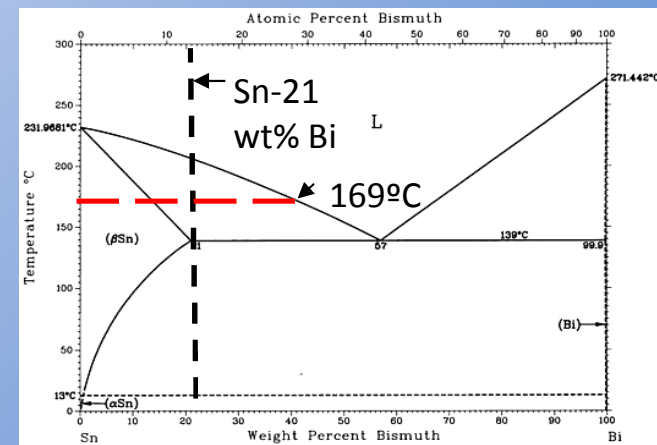
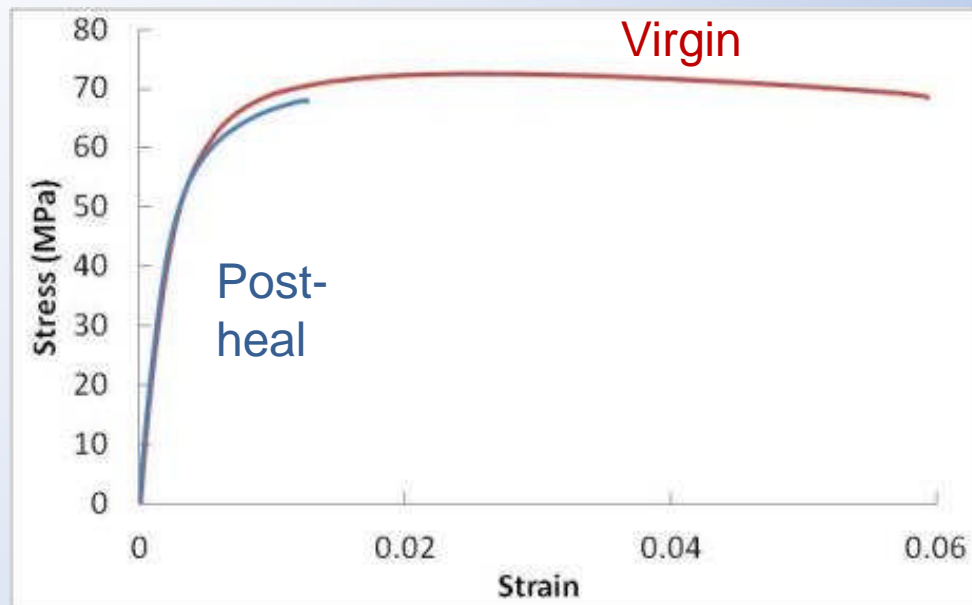
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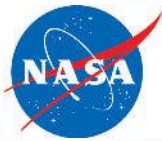
Liquid-Based Healing History

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- Healing of cm-long cracks has been achieved in a proof-of-concept Sn-Bi matrix reinforced with Ni-Ti SMA wires
 - Healing treatment: 20% liquid in matrix
 - Post heal: 95% strength recovery (UTS)



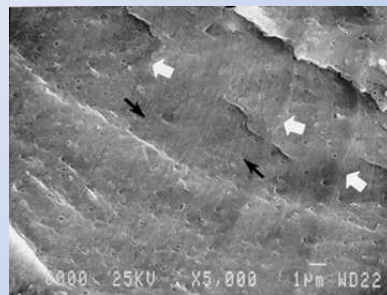
Manuel, et al, "Design Considerations for Matrix Compositions in Self-Healing Metal Matrix Composites."
3rd International Conference on Self-Healing Materials; June 27-29, 2011; Bath, England.



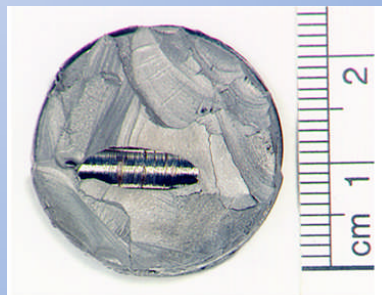
Knowledge Gap

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- POC material showed liquid-assisted self-repair of overload cracks
 - Will self-healing work with a higher strength structural material?
 - Will liquid-assisted self-repair work for repairing fatigue cracks?
 - How is fatigue life affected by this technology?



Fatigue striations from the Tail Cone Gap Cover.
Scanning Electron Microscope (SEM). Magnification: 5,000X



Macrographic view of confluence point fracture surface displaying extensive fatigue damage.

*McDanel et al, NASA KSC
Failure Analysis and Materials Evaluation*



Applications

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- Aerospace-grade aluminum materials subject to cyclic loading are susceptible to fatigue failure, sometimes catastrophic, at loads well below yield strength.
- Wrought and cast Al alloys used throughout aircraft:



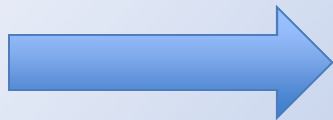
Heinimann et al, Alcoa, "Advanced Metallic and Hybrid Structural Solutions for Light-Weight, Long-Lived Aerospace Structures
Aircraft Airworthiness & Sustainment Conference 2012



Impact of Innovation

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- Improve damage tolerance and fatigue life of metals at critical structural locations
- Alternative to conventional repair techniques of fatigued structures
 - Mechanically fastened, bonded, etc.
- Integrated self-repairing approach would improve durability and sustainability of the aerospace material to ensure vehicle safety



Implications could revolutionize the industry and other NASA programs



Technical Approach

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- The principal objectives of Phase I:
 1. Fabricate a high specific strength aluminum-based metal matrix composite that can repair cracks using liquid-assisted self healing
 - a. Targeting specific microstructural constituents based on thermodynamics and kinetics of the system.
 - b. Testing various fabrication techniques for optimal performance
 2. Characterize the mechanical behavior of the novel aluminum matrix constituent and composite before and after healing
 - a. Primarily tensile and fatigue testing
 3. Explore and optimize the reinforcement architecture for composites reinforced in a uniaxial and cross-ply orientation.



Phase I Results

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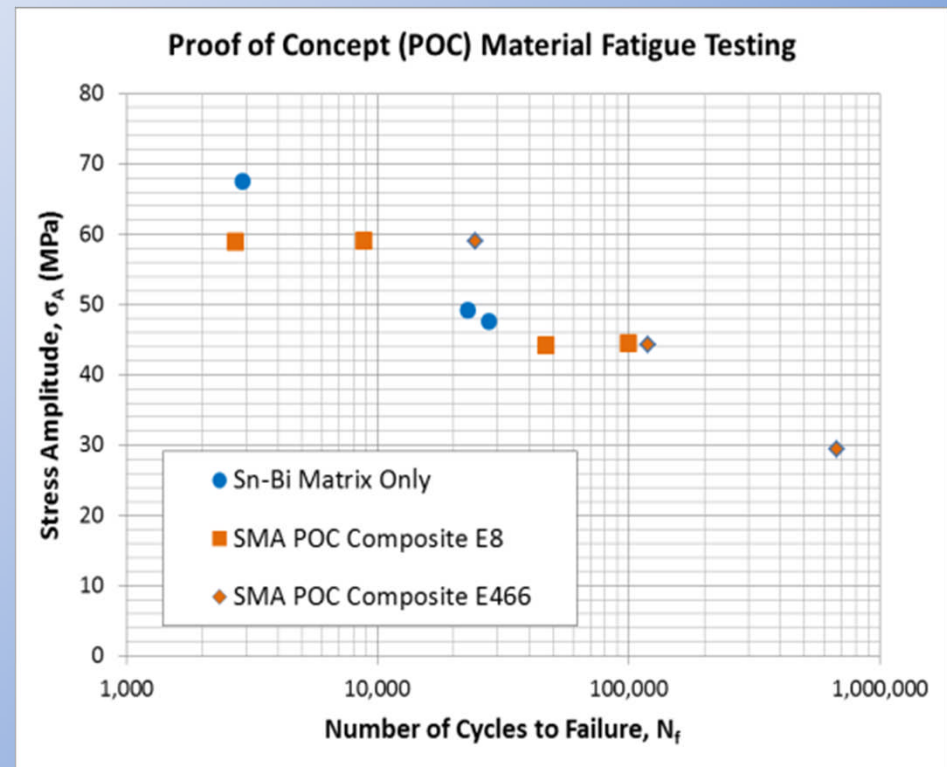
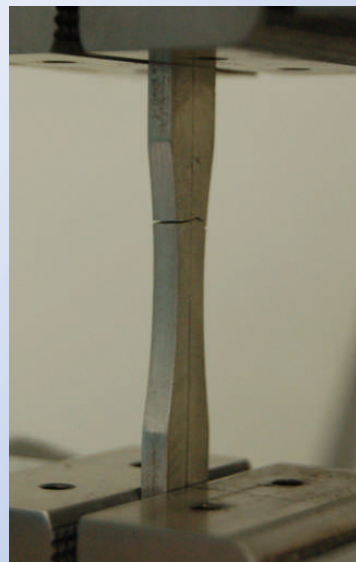
- Fabricated, tested, and healed overload and fatigue cracks in proof-of-concept tin-bismuth (Sn-Bi) composite.
- Proved self-healing in a cast binary Al-Si matrix alloy with pre-determined eutectic phase and 2 vol% Ni-Ti SMA wires.
- Fatigue tested the self-healing binary Al-Si alloy to create a stress life (S-N) curve.
- Fabricated two Al-Cu alloys with a pre-determined eutectic phase for self-healing: binary Al-Cu & ternary Al-Cu-Si.
- Fabricated multi-ply test samples of Al-Cu-Si alloys by isostatically hot pressing thin slices of the matrix and sandwiching SMA reinforcements at the interface.



Results: POC Material

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- Fatigue tested proof-of-concept tin-bismuth (Sn-Bi) material to establish use of technology for cyclically loaded applications.

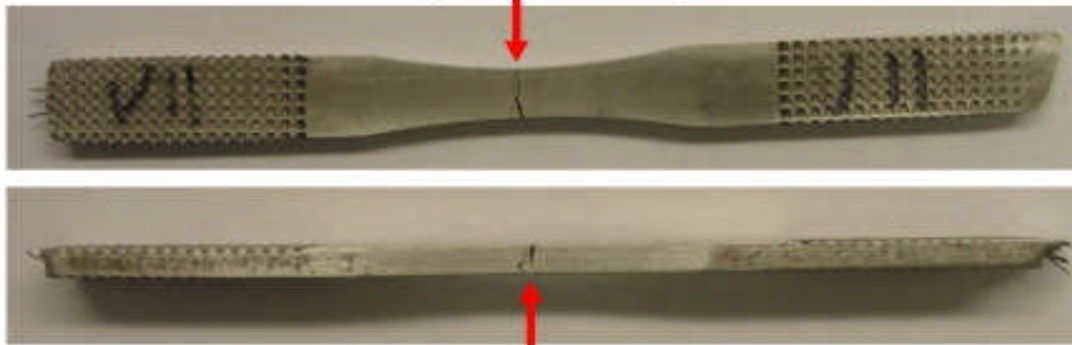




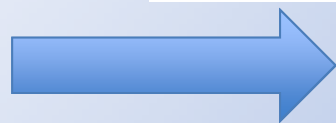
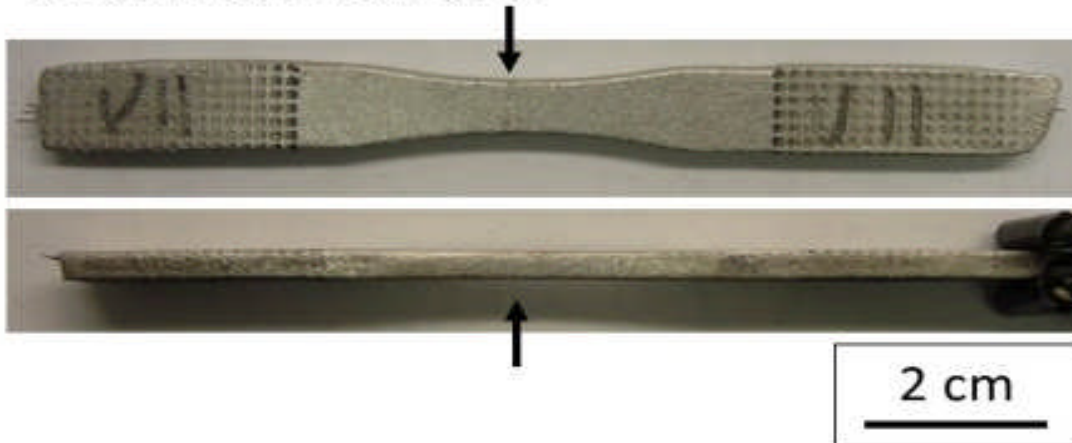
Healing Fatigue Crack in POC

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Before: Post-Fatigue Testing at KSC



After: Post-Heal at UF



Proved healing of fatigue crack in POC

July 9-11, 2013

NASA Aeronautics Mission Directorate FY12 Seedling Phase I Technical Seminar

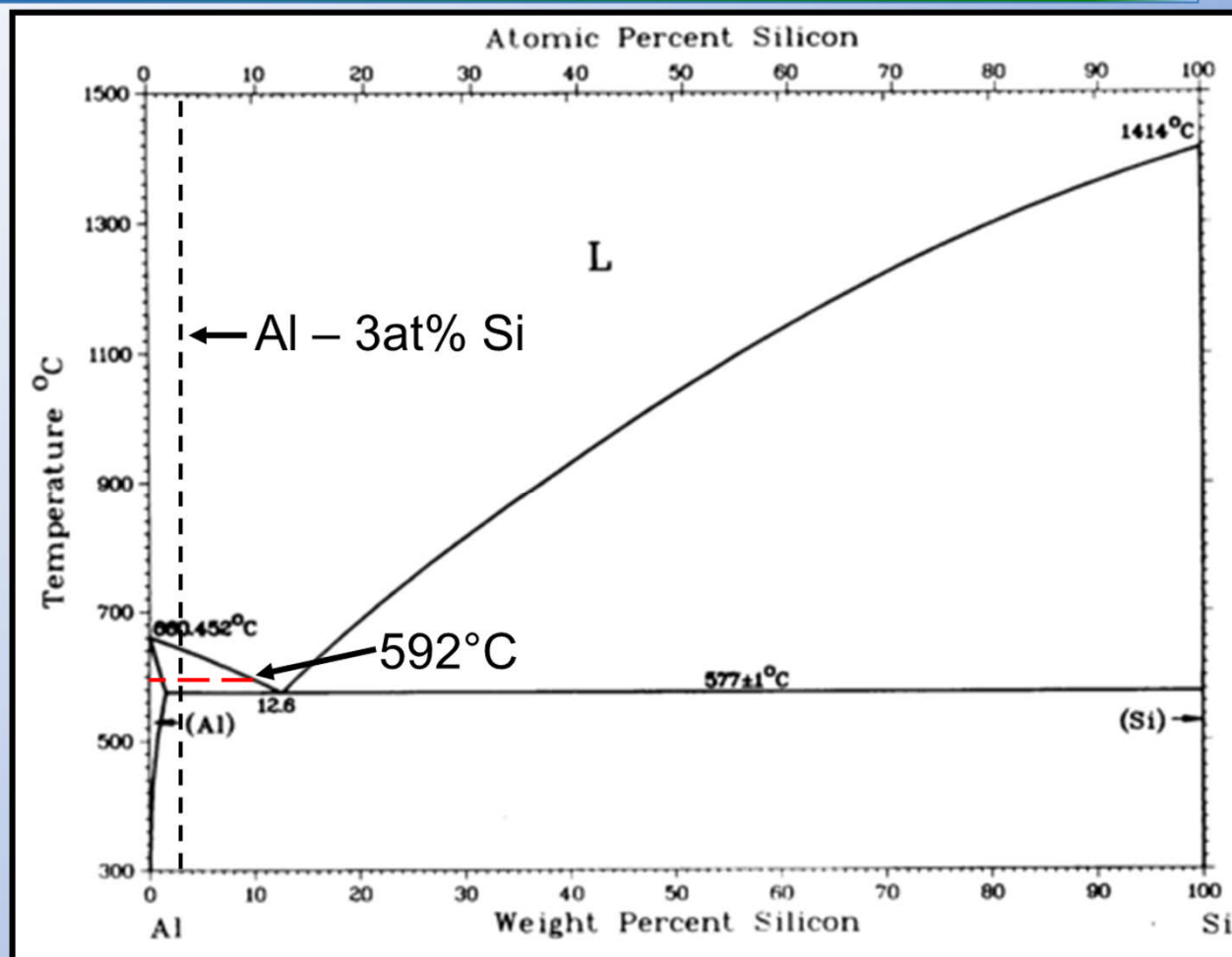
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Systematic Alloy Design

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- Thermodynamic approach used to design binary alloy.
 - Castability
 - Eutectic Temp
 - Strength
- Samples were cast in graphite mold

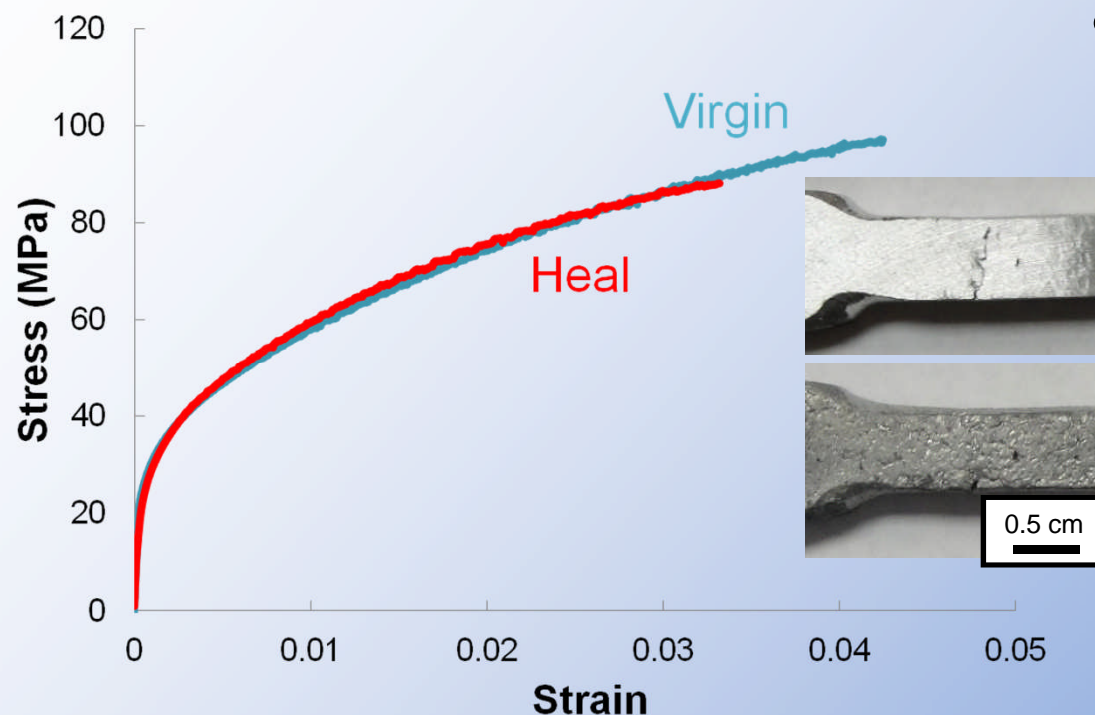


Manuel et al, "Design Methodology for Liquid-Assisted Self-Healing Materials"
4th International Conference on Self-Healing Materials, Ghent, Belgium, June 2013

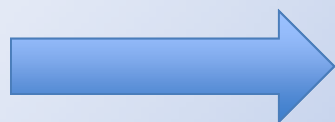


Healing in Al-Si alloy

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- Binary Al-3Si cast at 750°C;
 - 2 vol% NiTi SMA wires
 - Microstructural stabilization heat treatment
 - Tensile tested, healing treatment, tensile tested again



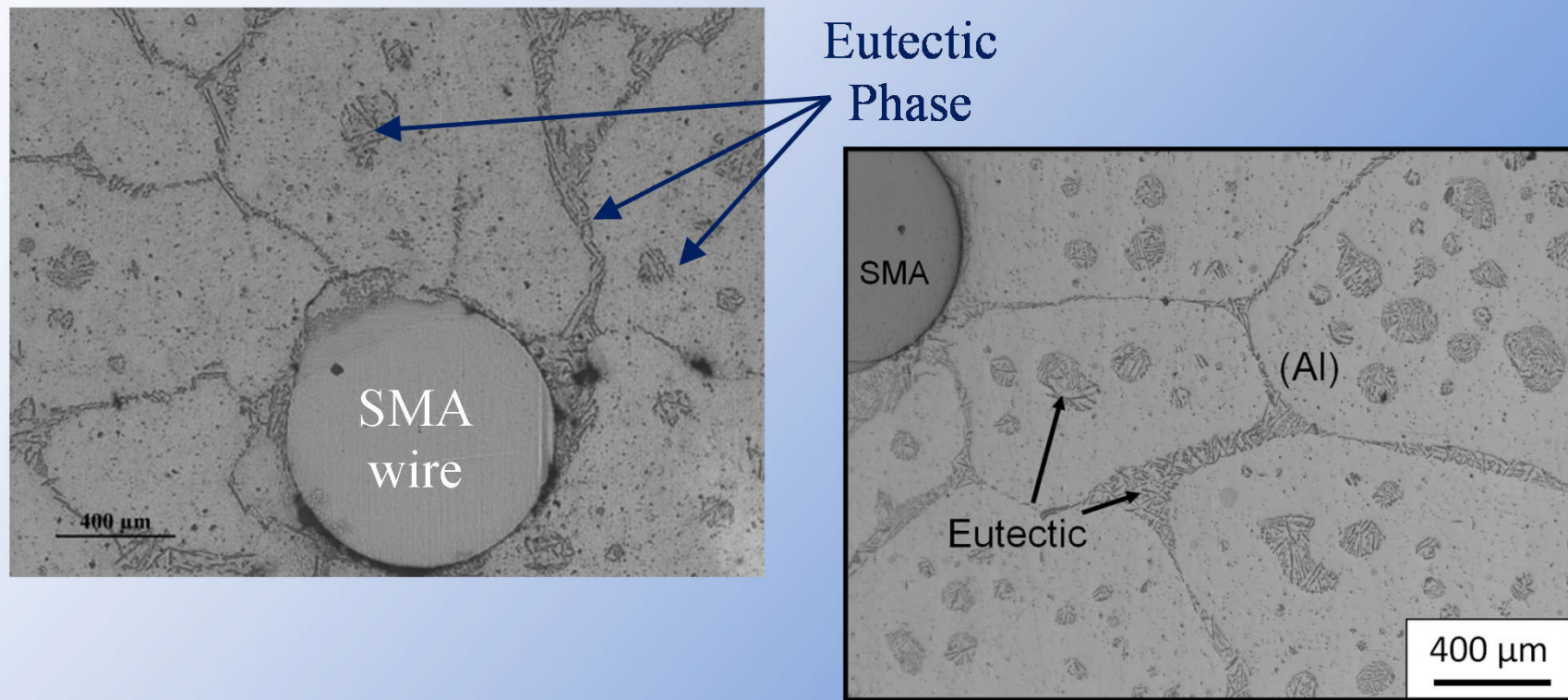
Proved self-healing with over 90% UTS recovered



Results: Healing in Al-Si

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- Microstructure showed uniform eutectic phase distribution and adequate wire bonding.
 - Eutectic phase distribution ideal for liquid-assisted healing

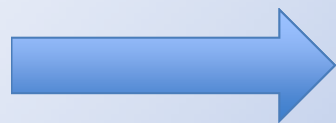
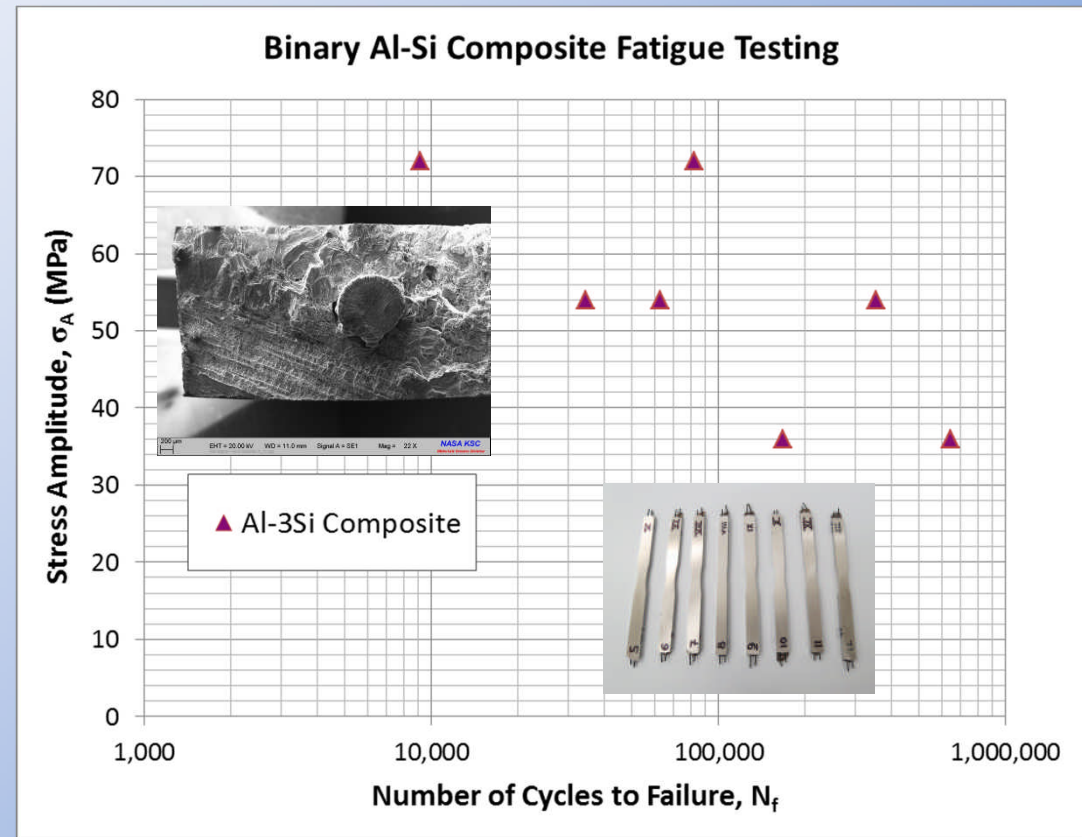




Results: Al-Si Fatigue Behavior

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- Fatigue tested the self-healing binary Al-Si alloy to create a S-N curve.
 - Significant variability in data due to porosity from fabrication technique
 - No effect of fatigue loading on SMA wires



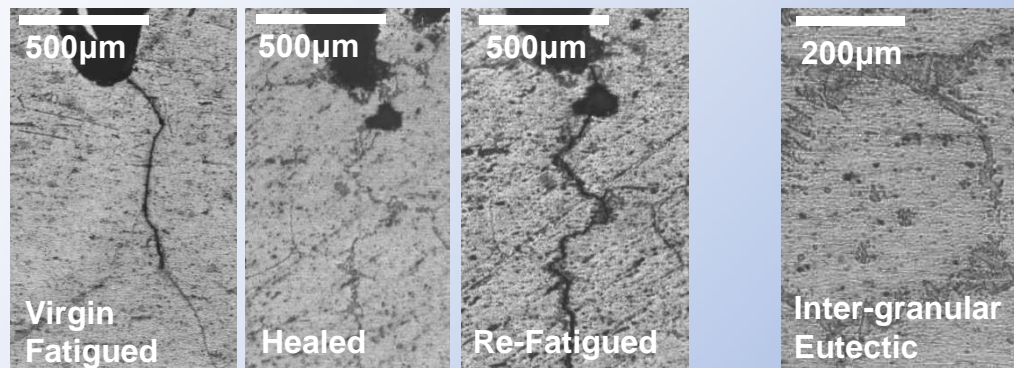
Cast binary alloy fatigue behavior was determined



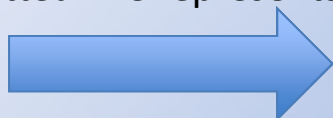
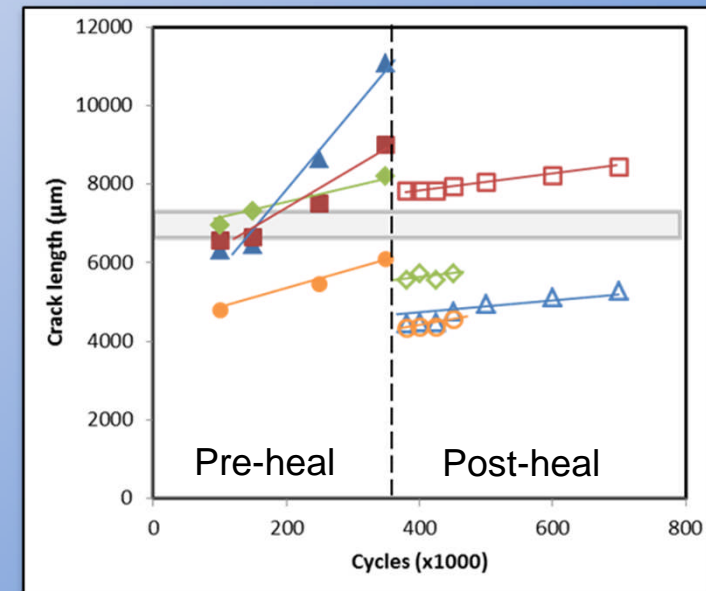
Results: Al-Si Fatigue Behavior

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- Conducted fatigue crack growth tests on middle tension M(T) and single edge notch tension ESE(T) specimens to grow and heal a small fatigue crack.
 - Cracking occurs preferentially through eutectic along grain boundaries both pre- and post- healing.



- Healing of micron-scale fatigue cracks, as well as macro-scale machined notches achieved
- Fatigue crack growth rate decreased after healing; dotted line represents healing treatment



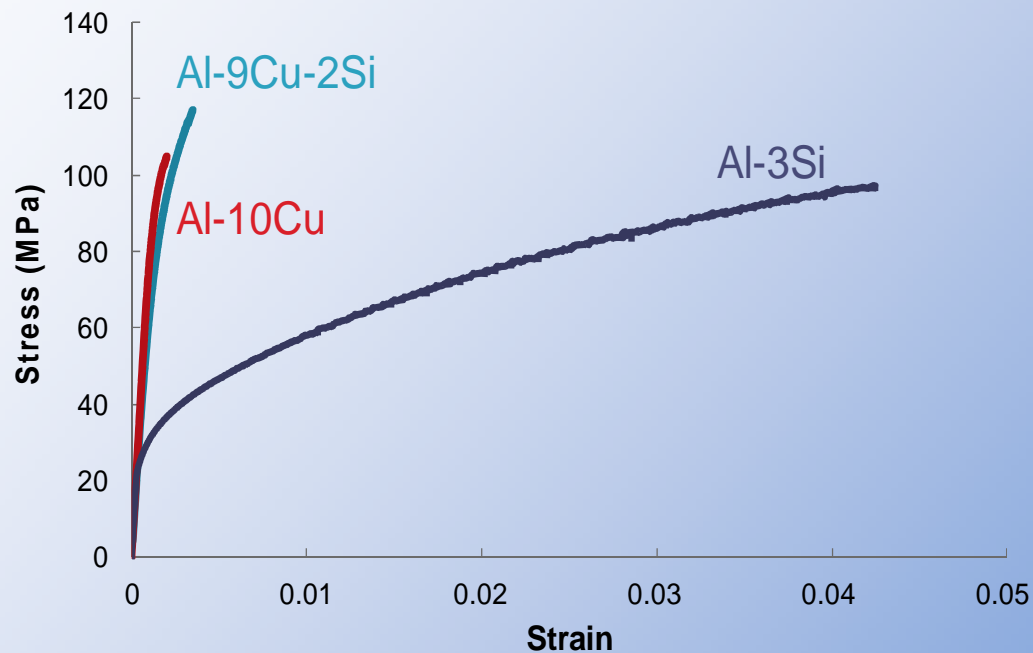
Healed binary Al alloy fatigue crack



Results: Al-Cu alloys

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- Fabricated two Al-Cu alloys with a pre-determined eutectic phase for self-healing:
 - Binary Al-Cu & ternary Al-Cu-Si.



- Al-Cu alloys more brittle than the Al-3wt%Si in tension
- Little healing was evident in either Al-Cu or Al-Cu-Si alloys.
- It is theorized that the lack of ductility did not allow for the martensite → austenite transition within the SMA wire, and therefore no closure force was put on the matrix from the SMA wire.
- Without a clamping force to close the fracture faces, healing was unable to occur.



Results: Diffusion Bonding Fabrication

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- Fabricated multi-ply test samples of Al-Cu-Si alloys by isostatically hot pressing thin slices of the matrix and sandwiching SMA reinforcements at the interface for diffusion bonding.
 - Eliminates casting defects
 - Potential for improved strength and ductility
 - Composites with more complex wire geometries can be fabricated

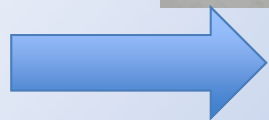
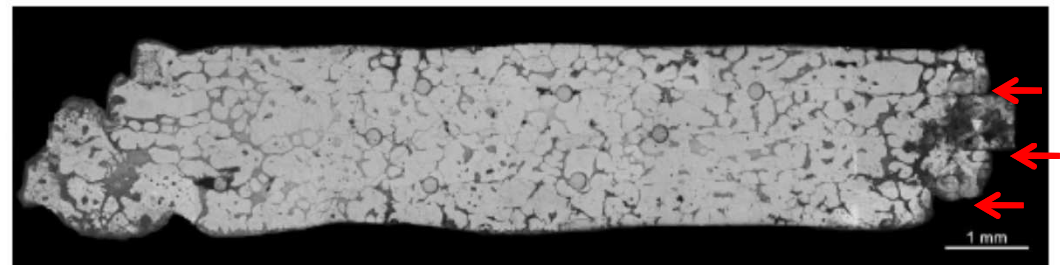
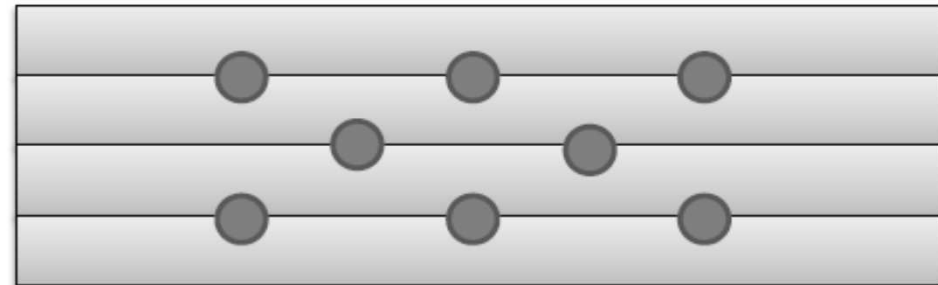
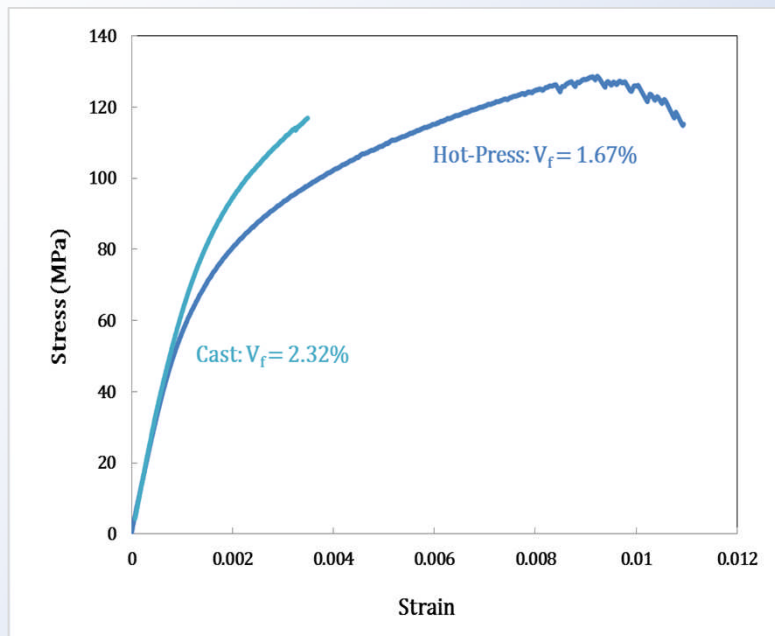




Multi-ply Specimens

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- Up to four plies with three reinforcement layers at the interfaces were successfully fabricated.



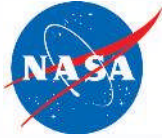
**Viable fabrication technique for multi-ply specimens
was established**



Distribution/Dissemination

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- Submitted for NASA New Technology Report for future patent application.
- International Conference of Self Healing Materials, Ghent, June 2013, *Design Methodology for Liquid-Assisted Self-Healing Metals*.
- Team will also continue to present results at relevant technical presentations (MS&T 2013, TMS 2014), write at least one peer-reviewed journal article, and be submitted for inclusion in NASA technical publications such as Tech Briefs.
- The technology will be showcased at KSC's next innovation day.



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Next Steps

- Phase II research will include:
 - Full development and characterization of the fatigue life behavior of the Al-Cu base alloys fabricated with unidirectional, multi-ply SMA reinforcements.
 - Modeling of the multi-ply specimens to determine optimal wire reinforcement and SMA clamping forces for healing using SMA-specific finite element analysis (FEA).
 - Fabrication of multi-ply specimens with optimal wire reinforcement and heat treatment to demonstrate multi-axis crack closure and healing of tensile and fatigue cracks.

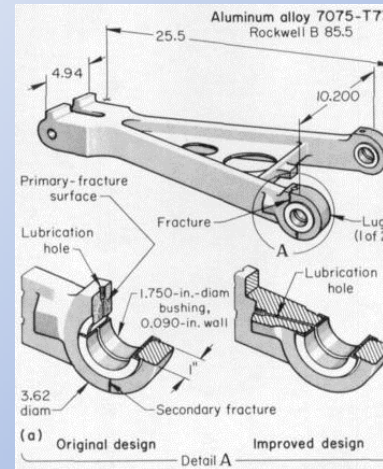


Optional Funding

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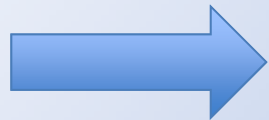
- Design, model, and fabricate a small scale prototype with more complex geometry based on vehicle parts that have shown a history of fatigue cracking in the field.

ASM Failure Analysis Center, Case Histories in Failure Analysis, 2024-T3



Aluminum alloy 7075-T73 landing-gear torque-arm assembly that was redesigned to eliminate fatigue fracture at a lubrication hole.

Nose wheel fork failed when plane was in service.



Team is requesting the additional \$75K to create a self-repairing prototype and bring TRL to 4.



- KSC – project management, fatigue testing, characterization
- LaRC – specimen fabrication, healing
- University of Florida – master alloy creation, fabrication, testing, healing of tested specimens
- Northwestern University – FEA models

